Hindawi
Journal of Advanced Transportation
Volume 2022, Article ID 5425895, 8 pages
https://doi.org/10.1155/2022/5425895

Research Article

A Route Choice Model for Road Network Users in Mountainous Cities considering Vulnerability

Lei Wu and Baichuan Lu

School of Traffic & Transportation, Chongqing Jiaotong University, Chongqing 400074, China

Correspondence should be addressed to Lei Wu; wulei@cqjtu.edu.cn

Received 18 November 2021; Accepted 13 January 2022; Published 15 March 2022

Academic Editor: Yang Yang

Urban resilience has become one of the core arguments of sustainable urban development. The urban road system should also respond effectively to various changes or impacts and reduce the uncertainty and vulnerability of road network caused by emergencies. A route choice model considering the vulnerability was proposed. The model analyzed the traveler' behavior in complex road network. The model is validated by the road network in Chongqing city. First, the vulnerability of road network in mountainous cities is defined, and the failure situation and state classification of road network considering vulnerability are analyzed. The results show that travelers with different sensitive states have obvious different route choice behavior in vulnerable networks. Since nonsensitive users do not reserve travel time in the early days, they are more inclined to respond to emergencies quickly and then choose fast detour paths. However, sensitive users have set off earlier than normal time and have psychological expectations of emergencies. They have more time to maintain the existing path. Finally, a calculation example is used to test that a certain section of the road network fails randomly, and network users can effectively choose the individual optimal route under different failure states.

1. Introduction

There are many factors influencing the route choice of travelers, such as the road length, travel time, toll policy, congested status, and traffic reliability. When travelers choose a route, they mainly consider travel time, reliability of travel time, and path length.

To take all factors into account, scholars usually convert them into travel costs. While travelers may pay more attention to the reliability of travel time or the vulnerability of the road section, that is, to avoid the traffic reliability problems caused by some sections, such as sudden conditions, congestion, and bad weather, to be able to reach the destination more accurately, travelers often set off earlier than the expected time to minimize the possibility of not being able to arrive on time and to improve the reliability of arriving. Generally, the urban road network is affected by many factors, and the vulnerability of road network is an important factor affecting the traffic reliability. The stronger the necessity of travel is, the more the possibility of early departure. Therefore, many scholars introduce travel time reliability into the index of route choice by studying the vulnerability of the road network.

System vulnerability assessment methods can be divided into four categories: the scenario analysis method, strategy analysis method, simulation method, and mathematical simulation method [1]. There is the most vulnerability assessment research based on the scenario analysis method. The scenario analysis method is usually used to describe all possible scenarios. Sohn et al. used this method to evaluate the importance of the Maryland highway network under flood disaster [2]. Based on the scenario analysis method, Arşık studied the failure of highway sections under earthquake disasters, but it lacked the consideration of interaction, and the ability to describe the local and internal attributes of the network was weak [3]. Gao et al. proposed a method to measure road network vulnerability by using discrete Ricci curvature, which can identify key road sections and display their vulnerable units [4]. However, from the perspective of network vulnerability, the network has the main body failure and the failure of connected links in different degrees. The exhaustive method has low computational efficiency, which is not suitable for the comparative analysis of large-area road network failure and the performance of different networks.

The strategy analysis method can analyze the network vulnerability to one or several road sections failure. The common method is to sort the road sections or nodes in the network according to the importance and then delete the road sections or nodes separately according to the results and calculate and record the change of network performance each time. Albert et al. used this method to study the structural vulnerability of North American power grid [5], but this method can only be limited to the hypothetical attack strategy and cannot exhaust all kinds of possibilities like the scenario analysis method.

Simulation evaluation method is to simulate various scenarios using simulation software and calculate vulnerability evaluation indexes according to simulation results. Yin et al. proposed the framework of vulnerability measurement and improved model of road network structure and defined the road network structural vulnerability using the network efficiency model [6]. Singh et al. provided a framework for vulnerability assessment of urban road network, linking flood depth with deceleration to determine the vulnerability of road network [7]. Berdica et al. used the simulation software tracks, Saturn and Paramics, to simulate the network travel time and network travel distance when the traffic was interrupted. Through sensitivity analysis, Paramics was considered to be the most suitable for simulating short-time disturbance [8].

The data model evaluation method is to judge vulnerable road sections by building some models or expressions. Zhang et al. used system science and the complex network theory to abstract the topological structure of urban rail transit network, analyzed its connectivity, and studied the static and dynamic vulnerability based on traffic function [9]. Zhang et al. studied the urban rail transit network based on the dynamic time-varying characteristics of topological complexity at the hourly scale [10]. Wu et al. introduced the fault tolerance index of metro system vulnerability from the perspective of passengers [11]. Matisziw et al. built a goal programming model to evaluate the potential traffic of all paths between node pairs [12].

The relationship between road network vulnerability and network traffic flow is reflected in the impact of vulnerability on the decision-making behaviors of travelers and the impact of traffic network reliability on network traffic flow. The aggregation behavior of many travelers forms a traffic flow state, which is the result of traffic flow assignment. The former is route choice behavior modeling based on road network reliability, and the latter is traffic network assignment problem based on vulnerability. Most of the travelers are risk averse. To deal with the lateness caused by congestion, they usually set off ahead of time. At the same time, they prefer the reliable path to the shortest path when choosing route [13]. Traditional risk aversion research method is to study the decision-making behavior of travelers in the framework of expected utility, combining with travelers' behaviors, reliability index and the index describing risk preference of travelers. Zhang et al. proposed a new method to estimate network traffic flow [14], which integrates traffic records and crowd sourcing data into a geometric matrix completion model.

Based on the above researches, a route choice model based on many reliability indexes is proposed, which studies the factors that will lead to the random changes of traffic demand and section capacity and considers the user equilibrium allocation based on reliability. The presuppositions include random change of demand or capacity [13], random change of supply and demand [15], or prediction technology based on deep learning algorithm [16–21]. Usually, considering the reliability, the route choice of travelers is often considered from two aspects [22]. One is to add the reliability index to the link impedance function to construct the generalized travel cost so as to affect the route choice; second, according to the different reliability requirements of travelers, the user equilibrium traffic assignment model is established by defining the relevant reliability indexes as the route choice criteria.

The rest of the paper will be organized as follows. First, we give a thorough review of the research method. In Section 3, we detail the proposed model and the structure. We discuss the result compared with the results of other models. In Section 4, it is the conclusion.

2. Research Method

2.1. Definition of Traffic Network Vulnerability in the Mountainous City. The vulnerability of the mountain city traffic network refers to the sensitivity of the system to abnormal events that can significantly reduce the performance of the mountain city traffic system. These abnormal events can be predictable or unpredictable, inevitable or accidental, and man-made or natural. Compared with ordinary cities, the road network in mountainous cities has the characteristics of high nonlinear coefficient, large slope, few replaceable roads, and high road interchange probability. There are few alternative roads, resulting in fewer alternative paths in case of traffic congestion. From the perspective of driving behavior and path selection behavior, less optional paths or more detours will affect the driver's low expectation intensity of changing the path in the face of vulnerability events.

The main components of traffic network vulnerability in mountainous city include the probability of the function failure caused by the occurrence of hazardous events in the nodes, sections and the whole system of the traffic network in mountainous city and the consequences. The definition of hazardous events includes small probability emergencies and normal hazardous events. As for the measurement of the consequences, it mainly studies the generalized cost and delay of the vehicles in the urban transportation network.

2.2. Analysis of Road Section Failure Based on Network Vulnerability. Road section failure in mountainous city caused by the vulnerability mainly in the following aspects:

one is bad weather or traffic control, which reduces the speed limit of the road, reduces the traffic capacity and causes congestion due to partial failure of the road section. The other is that the sudden traffic accidents in some sections lead to the closure or partial closure, resulting in a sudden drop in traffic capacity. There may be two failure states: complete failure and partial failure. The failure probability of the road section is defined as the probability of failure state.

When the road emergency, bad weather, or road maintenance directly led to the closure of road, or part of the lane closed, it is called the complete failure of the road section. If the capacity of the road section is affected but still retains part capacity, the road section is in a partial failure state. Complete failure and partial failure will have an important impact on the traffic flow of the whole network. Total failure has a great impact on the road network. If the road section is in failure for a long time, some travelers will consider route re-selection, and the network traffic flow will be redistributed to form a new equilibrium state.

The node deletion method is widely used in the road network vulnerability, which is simple and practical. However, after the failure of a certain road section, the diffusion effect of failure is not considered, which leads to the inconsistency between the characterization of road network vulnerability and the facts. To characterize the capacity of the invalid section or adjacent area of the node, the existing node deletion method is optimized. Therefore, the first step is to collect the network information and abstract the network topology as an adjacency matrix. The required section information includes section length, number of lanes, and travel speed, which is used to calculate section capacity and section impedance (the BPR function is used for impedance, see the model for details). When there is no section failure, the initial traffic is allocated according to the user equilibrium model. Based on the known capacity and initial flow, the initial impedance is calculated. If a section i fails or partially fails, the impedance of that section will be directly affected. Meanwhile, the impedance of other directly related sections will also be affected to a certain extent, and the traffic capacity will be reduced. Define θ_a as the section failure reduction factor, and $\theta_a \in [0, 1]$. If section a is a mandatory failure, θ_a is reduced. If it is completely forced to fail, then $\theta_a = 0$. If partial forced failure occurs, $\theta_a \in [0, 1]$, and if it does not fail, $\theta_a = 0$. The traffic volume is allocated again according to the user equilibrium model to obtain the new section traffic, and the total network travel time is calculated based on the new section flow and impedance. If the traffic demand of an OD pair cannot be met, record the trip volume of the OD pair. Every section failure traverses all OD pairs. After calculating the failure consequences of a section, it turns to the next section until all section s are traversed. The principle of the improved node deletion method is shown in Figure 1. The main process and content of the model are shown in Figure 2.

The black link represents the normal section, the red link represents the failed section, and the pink link represents the associated section. When a section fails or partially fails, its associated section will also be affected and be in a partial failure state.

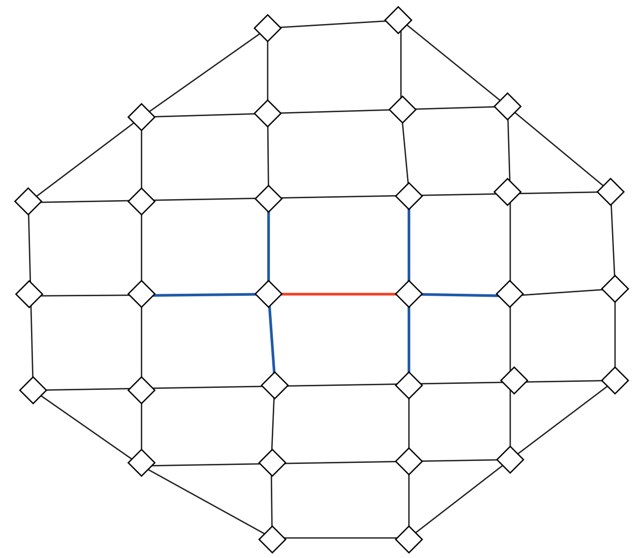

Figure 1: Schematic diagram of the algorithm.

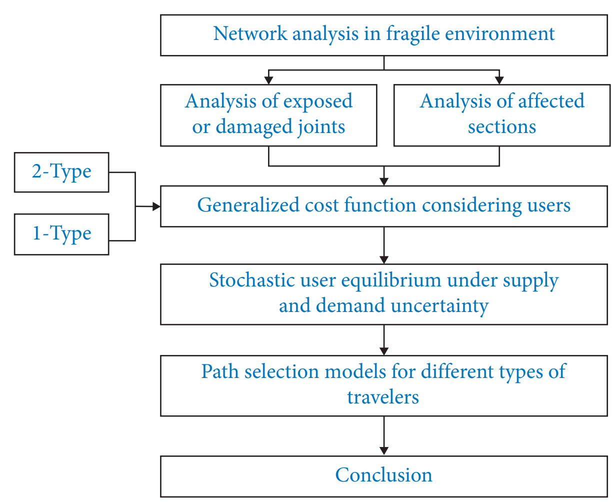

Figure 2: Outline of the proposed method.

3. Traveler Route Choice Model Based on Network Vulnerability

3.1. Modeling. Due to the complexity of the road network in mountainous cities, the network vulnerability leads to the great changes of travel time for some travelers. The travelers who take the lower limit of travel time tolerance as the route choice criteria think that the reason for the increase of travel time is the mutation of section capacity. In mountainous cities, the road line is tortuous, and the set of alternative roads is less. Once a road or intersection accident occurs, there will be a certain degree of interference to the road capacity, causing a sudden drop in the capacity of local road network. It leads to the travelers not obtaining relevant information in time before and during the trip, and the overall travel time reliability is reduced. To arrive at the destination on time, travelers who have urgent travel and time usually reserve a travel time threshold based on the average travel time to deal with the traffic congestion caused by emergencies. The section impedance function is calculated by the BPR function in (1).

$$T_a = t_a\left[1+\beta_a\left(\frac{v_a}{C_a}\right)^n\right]. \quad (1)$$

The free flow travel time of different road sections t_a, parameters β, and n have been determined. C_a is the capacity of road section; v_a is the traffic volume of road section, and T_a is the section impedance. Suppose that C_a obeys the uniform distribution on $[\theta_a C_a, C_a]$. According to the aforementioned formula, the mean and variance of T_a can be expressed as (2) and (3):

$$E(T_a) = E(t_a) + \beta_a E\left[t_a\left(\frac{v_a}{C_a}\right)^n\right] = t_a + \beta_a t_a v_a^n E\left(\frac{1}{C_a^n}\right), \quad (2)$$

$$\operatorname{var}(T_a) = \operatorname{var}(t_a) + \beta_a^2 t_a^2 \operatorname{var}\left[\left(\frac{v_a}{C_a}\right)^n\right] = \beta_a^2 t_a^2 v_a^{2n} \operatorname{var}\left(\frac{1}{C_a^n}\right). \quad (3)$$

Due to the emergencies of local nodes in the road network, considering the vulnerability of local section C_a in the network obeys the uniform distribution, then we can calculate that if $n=1$, then we can get equations (4) to (9):

$$E(T_a) = t_a + \beta_a t_a v_a E\left(\frac{1}{C_a}\right) = t_a + \beta_a t_a v_a \frac{2}{C_a(\theta_a+1)}. \quad (4)$$

If $n \neq 1$, and

$$E\left(\frac{1}{C_a^n}\right) = \int_{\theta_a C_a^m}^{C_a^m} \frac{1}{C_a^n}\frac{1}{C_a^m(1-\theta_a)} \mathrm{d}C_a = \frac{1-\theta_a^{1-n}}{C_a^{n,m}(1-\theta_a)(1-n)}, \quad (5)$$

$$E\left(\frac{1}{C_a^{2n}}\right) = \int_{\theta_a C_a^m}^{C_a^m} \frac{1}{C_a^{2n}}\frac{1}{C_a^m(1-\theta_a)} \mathrm{d}C_a = \frac{1-\theta_a^{1-2n}}{C_a^{2n,m}(1-\theta_a)(1-2n)}, \quad (6)$$

$$\operatorname{var}\left(\frac{1}{C_a^n}\right) = E\left(\frac{1}{C_a^{2n}}\right) - E^2\left(\frac{1}{C_a^n}\right) = \frac{1-\theta_a^{1-2n}}{C_a^{2n,m}(1-\theta_a)(1-2n)} - \left[\frac{1-\theta_a^{1-2n}}{C_a^{n,m}(1-\theta_a)(1-n)}\right]^2, \quad (7)$$

$$E(T_a) = t_a + \beta_a t_a v_a^n \frac{1-\theta_a^{1-n}}{C_a^{n,m}(1-\theta_a)(1-n)}, \quad (8)$$

$$\operatorname{var}(T_a) = \beta_a^2 t_a^2 v_a^{2n}\left\{\frac{1-\theta_a^{1-2n}}{C_a^{2n,m}(1-\theta_a)(1-2n)} - \left[\frac{1-\theta_a^{1-n}}{C_a^{n,m}(1-\theta_a)(1-n)}\right]^2\right\}. \quad (9)$$

Assuming that the section capacity is independent to each other, the travel time variable between OD and w can be expressed in (10) as the section variable.

$$T_{rw} = \sum_{a\in A}\delta_{ar}T_a. \quad (10)$$

According to the central limit theorem, the path travel time T_{rw} obeys the normal distribution, and its mean and variance are given as

$$T_{rw} \sim N\left(E(T_{rw}), \sigma_{T_{rw}}\right) \sim N\left(\sum_{a\in A}[\delta_{ar}E(T_a)], \sqrt{\sum_{a\in A}[\delta_{ar}E(T_a)]}\right). \quad (11)$$

The travel time of travelers can be expressed as

$$B_{T_{rw}} = E(T_{rw}) + \lambda\sigma_{T_{rw}}, \quad w \in W, \quad (12)$$

where $B_{T_{rw}}$ is the estimated travel time of the r-th route between OD and $w \in W$. λ is the sensitive parameter of the traveler, and its value is related to the travel purpose and requirements, that is, the traveler is willing to bear the delay caused by the road network vulnerability. If the travelers have high requirements for on time arrival, that is, the users are sensitive users. Usually, the travelers reserve a large $B_{T_{rw}}$

value, that is, require λ take a large value. For those travelers who are not strict with the time requirement, that is, nonsensitive users, such as shopping and playing, the λ is small. The concept of arrival in λ can be expressed as

$$P\left\{T_{rw} \le B_{T_{rw}}\right\} = P\left\{\frac{T_{rw} - E(T_{rw})}{\sigma_{T_{rw}}} \le \lambda\right\} = \alpha. \quad (13)$$

Among them, α is the reliability requirement for the arrival of travelers, that is, the introduction of accurate arrival within the budget time, $\alpha = \Phi(\lambda)$, or $\lambda = \Phi^{-1}(\alpha)$, where $\Phi(.)$ represents a normal distribution random variable distribution function. If $\alpha = 95\%$, then $\lambda = 64$, which means that the probability of the traveler arrival is 95%. According to the monotonically increasing nature of the function, the larger the λ is, the larger the travel time budget, and the higher the reliability α of arrival within the budget time. In a physical sense, λ indicates the sensitivity of travelers, the larger the λ, the more travel time may be reserved, the higher the reliability of arriving on time, the lower the vulnerability of road network, and the lower the tendency of changing the existing path.

The road sections and traffic flow of urban road network are expressed in (14) and (15):

$$v_a^m = \sum_w \sum_r f_{rw}^m \delta_{ar}, \quad \forall a \in A, m = 1, 2, \ldots, M. \quad (14)$$

$$v_a = \sum_m v_a^m, \quad \forall a \in A. \quad (15)$$

The restriction conditions of flow are shown in (16) and (17):

$$\sum_r f_{rw}^m = d_w^m, \quad \forall w \in W, m = 1, 2, \ldots, M_, \quad (16)$$

$$u_{rw}^m = u_a^m(v)\delta_{ar}, \quad \forall r \in R_W, w \in W, m = 1, 2, \ldots, M, \quad (17)$$

where when r contains a, $\delta_{ar} = 1$, otherwise $\delta_{ar} = 0$. The utility function of the m-traveler on the route r between OD pairs is defined in (18)

$$u_{rw}^m = E(T_{rw}) + \lambda_m \sigma_{T_{rw}}. \quad (18)$$

According to the different sensitivity of travelers to the random change of road capacity, urban travelers are divided into M categories. The more sensitive the traveler is, the greater the corresponding utility value will be. When the utility value is very small, it means that the traveler is not sensitive to the change. On the one hand, it is often difficult for travelers to choose multiple options; on the other hand, when the capacity of a road drops suddenly, it is difficult for travelers to switch paths quickly. To better simulate these behaviors, the utility function is transformed and the exponential utility function is used. It is shown in (19).

$$U_{rw}^m = \begin{cases} \dfrac{\exp(\lambda T_{rw})}{\lambda}, & \lambda \neq 0, \\ kT_{rw} + b, & \lambda = 0, \end{cases} \quad (19)$$

where k is positive number. T_{rw} is monotonically increasing and differentiable. No matter which kind of traveler, the greater the travel time is, the greater the utility value, and the lower the user satisfaction. Suppose the equivalent of utility function is $\mathrm{CE}_\lambda(T_{rw})$, then the relationship between the utility value and the expected value is

$$U(\mathrm{CE})_\lambda(T_{rw}) = E(U(T_{rw})). \quad (20)$$

It can be seen from the above formula that $\mathrm{CE}_\lambda(T_{rw})$ is a fixed value, there are shown in equations (21) to (24)

When $\lambda \neq 0$,

$$\frac{\exp(\lambda T_{rw})}{\lambda} = \frac{\exp(\lambda \mathrm{CE}_\lambda(T_{rw}))}{\lambda} = E\left(\frac{\exp(\lambda T_{rw})}{\lambda}\right), \quad (21)$$

$$\mathrm{CE}_\lambda(T_{rw}) = \frac{1}{\lambda}\ln(E(\exp(\lambda T_{rw}))). \quad (22)$$

When $\lambda = 0$,

$$\begin{aligned} k\mathrm{CE}_\lambda(T_{rw}) + b &= E(kT_{rw} + b), \\ \mathrm{CE}_\lambda(T_{rw}) &= E(T_{rw}), \end{aligned} \quad (23)$$

i.e.,

$$\mathrm{CE}_\lambda(T_{rw}) = \begin{cases} \dfrac{1}{\lambda}\ln(E(\exp(\lambda T_{rw}))), & \lambda \neq 0, \\ E(T_{rw}), & \lambda = 0. \end{cases} \quad (24)$$

According to the above-mentioned uniform distribution of capacity and normal distribution of travel time, we can get (25).

$$E(\exp(\lambda T_{rw})) = \exp\left(\lambda E(T_{rw}) + \frac{1}{2}\lambda^2\sigma_{T_{rw}}^2\right). \quad (25)$$

Substituting (25) into $\mathrm{CE}_\lambda(T_{rw})$, we can get (26).

$$\mathrm{CE}_\lambda(T_{rw}) = \begin{cases} E(T_{rw}) + \dfrac{1}{2}\lambda\sigma_{T_{rw}}^2, & \lambda \neq 0, \\ E(T_{rw}), & \lambda = 0. \end{cases} \quad (26)$$

Because $E(T_{rw})$ and $\sigma_{T_{rw}}^2$ have different dimensions, the equation only has physical meaning and can be used as the basis of decision-making. The utility function value is used as the basis of selection to determine the optimal route.

3.2. Model Solving Method and Example Analysis. According to the characteristics of the model, Multiple sequence alignment (MSA) algorithm [23] is used to solve the route choice model. The specific process is as follows:

(i) Step 1: Initialization. Input the traffic network OD of the mountainous city, and the travel reliability parameters α. The capacity limiting method is used to allocate the flow in stages to get the route flow f_{rw}^m, $\forall r \in R_w, w \in W, m = 1, 2, \ldots, M$, and the initial section flow v_a^1, $\forall a \in A$. n is iterations and $n = 1$.

(ii) Step 2: According to the current section flow $v_a^{(n)}$, $\forall a \in A$, update the utility function value of the route.

(iii) Step 3: On the basis of present route utility $U_{rw}^{m(n)}(v^n)$, the traffic assignment is carried out to obtain the route traffic, and then the auxiliary section traffic y_a^n, $\forall a \in A$ is obtained.

(iv) Step 4: Update the section flow using the following formula:

(v) Step 5: After iteration, if the result meets the convergence condition, the iteration will be stopped and the output result will be finished. Otherwise, let $n = n + 1$ and return to Step 1. It is shown in equations (27) and (28).

$$U_{rw}^{m(n)}(v^n) = E(T_{rw}(v^n)) + \lambda\sigma_{T_{rw}}(v^n), \quad \forall \in A, m = 1, 2, \ldots, M, \tag{27}$$

$$v_a^{n+1} = v_a^n + \frac{y_a^n - v_a^n}{n}, \quad \forall a \in A. \tag{28}$$

To verify the correctness of the model, a simple urban road topology network is designed as shown in Figure 3. It has five groups of OD, six nodes and 10 road sections. Five groups of OD are (1, 4), (1, 5), (1, 6), (2, 6), and (3, 5). The paths of all OD pairs are numbered in sequence, and there are 14 paths after analysis in Table 1. θ_a is the loss parameter of road section capacity; t_a^0 is the free flow travel time, c_a is the traffic capacity of section. $M = 2$, i.e. there were two types of travelers: sensitive (1-type) and nonsensitive (2-type), accounting for 50% of all OD pairs.

The travel time impedance of each link is shown in Table 1. For example, the time impedance value of link 1-2 is 128 s. The θ_a value corresponding to the link is 1.0, which means that the road section is not affected. The θ_a value of link 3-2 is 0.6, which means that the section is an accident section, and its traffic capacity is most affected by the accident.

For the convenience of calculation, let the travel demand of each OD be 25, the BPR parameter is used for the impedance of the section, $\beta_a = 1$ and $n = 4$. The free travel time t_a^0, design capacity c_a, and the degradation parameter θ_a of the road section are shown in Table 1.

According to the travel time, λ can be calculated. Assuming that the reliability of arrival in the budget time is 95%, and $\lambda = 64$, the reliability of arrival within the budget time is 50%, and the corresponding parameter $\lambda = 0$. By solving the model, the distribution results of route choice law with the minimum travel time as the selection rule under different road network conditions is shown in Table 2.

These two tables include the path selection of sensitive users and nonsensitive users for normal state ($\lambda = 1.64$) and vulnerability state ($\lambda = 0$). There are significant differences in route choice behavior among different types of travelers. Sensitive users are more sensitive to emergencies, more reserved travel time, and more acceptable delay, and more users tend to keep the existing route unchanged. The nonsensitive users have low estimation to the impact of emergency. Once the road section is broken or partially blown, the mentality is easier to change, and then the route can be adjusted in time and the subjective optimal route can be selected to bypass.

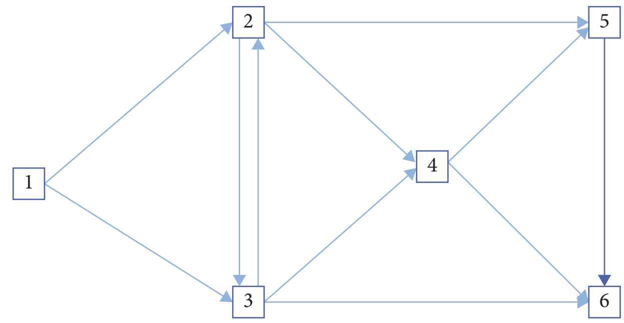

Figure 3: Simple urban road topology network.

3.3. Discussion. This paper describes the process of road network vulnerability analysis considering different types of people, from the conceptual definition of vulnerability measurement, through the derivation of practical indicators and models suitable for existing data, and their implementation in calculation programs and algorithms, to personalized path selection behavior, and finally to the application of this method in case studies. The document proposes that the vulnerability of road network is the social risk of road infrastructure interruption, and the impact of interruption scenario on individuals should be evaluated from an economic perspective. From this perspective, two aspects of vulnerability are distinguished, focusing on (I) users and (II) road networks. This paper introduces a case study of the Chongqing urban road network, in which single section closure and regional coverage interruption are considered.

Our results show that (1) the network connectivity of mountainous cities has an important impact on vulnerability and (2) the choice behavior of different people has an important impact on the redistribution of network traffic flow in case of emergencies in road network.

Under normal conditions, the total travel time of 1-type and 2-type on the road network is similar, 51587 s and 49225 s, respectively. However, due to the fragility of the network, the traffic capacity of some sections decreases, and some people change their travel paths. The travel time of people in the final 1-type is 87568 s, 34.8% lower than that of 2-type. At the same time, the distribution of the two types of people in the road network is also significantly different.

The results of these studies are consistent with those of Erik Jenelius [24] and others in terms of network connectivity [9, 25]. Jenelius conducted a vulnerability study on the road network of a city in Sweden. He studied the failure of only one road at a time and used driving time as a cost indicator. In his paper, we found that in sparsely populated, less populated and long travel time areas in Sweden, user contact is worse. Because the population in and around the CBD is less than that in the suburbs. Jenelius also found that

Table 1: Basic tables.

Sections	t_a^0 (s)	θ_a	c_a (pcu/min)
1-2	128	1.0	20
1-3	123	1.0	20
2-3	124	0.6	20
2-4	100	1.0	20
2-5	120	1.0	20
3-2	124	0.6	20
3-4	102	0.9	20
3-6	94	1.0	20
4-5	80	1.0	20
4-6	94	1.0	20
5-6	114	1.0	20

Table 2: Deterministic equivalent equilibrium flow mode with negative efficiency.

Od pair	No.	Path	Normal state route traffic			Vulnerability state route traffic		
			1-type	2-type	Travel time	1-type	2-type	Travel time
1-4	1	1-2-4	6.25	6.25	16 m 14 s	11	6.5	24 m 58 s
	2	1-3-4	6.25	6.25	11 m 04 s	1.5	6.0	1 h 39 m 15 s
1-5	3	1-2-5	7.5	12.5	18 m 12 s	12	10.5	25 m 8 s
	4	1-2-4-5	0	0	24 m 17 s	0.5	2	27 m 7 s
	5	1-3-4-5	5	0	19 m 7 s	0	0	1 h 44 m 50 s
1-6	6	1-3-6	6.25	12.5	14 m 16 s	6.25	12.5	13 m 10 s
	7	1-2-4-6	6.25	0	19 m 21 s	6.25	0	28 m 5 s
2-6	8	2-3-6	2.5	0	7 m 34 s	8.75	0	11 m 57 s
	9	2-4-6	1.15	12.5	9 m 12 s	1.15	12.5	13 m 15 s
	10	2-5-6	8.75	0	10 m 7 s	0	0	12 m 18 s
	11	2-4-5-6	0	0	16 m 12 s	2.5	0	14 m 17 s
3-5	12	3-4-5	6.25	12.5	10 m 19 s	0.5	7	1 h 39 m 15 s
	13	3-2-5	6.25	0	10 m 19 s	10.5	4.5	22 m 15 s
	14	3-2-4-5	0	0	16 m 24 s	1	1.5	24 m 14 s

the impact of total travel time on total risk is greater than the actual available alternative route network. Similarly, this is consistent with the vulnerability of highways in southeastern Sweden. Jenelius found that traffic has a greater impact on importance than physical network layout. Sally Freeman and others studied Adelaide network in Australia, which can explain that the main North Road and port road have higher importance value than Pulteney st to a certain extent. Urban networks tend to be denser and more connected than rural networks.

4. Conclusion

The road network of mountainous city is complex. Once an emergency occurs in a certain section, the network vulnerability will have a great impact on the travelers. From the perspective of network vulnerability, considering the law of network capacity loss under the random fusing of sections in the road network, the user route choice model of road network in the mountainous city is established. In the model, the factors of network vulnerability and traveler tolerance are fully considered, and the route choice behaviors of users are analyzed. The results show that the route choice behaviors of travelers in different sensitive states are significantly different in vulnerable networks. Nonsensitive users do not reserve more travel time in the early stage, so they are more inclined to respond to emergencies quickly, and then choose a fast detour route. The sensitive users have set off earlier than the normal time, and they have psychological expectations for emergencies, so they are more likely to maintain the existing route.

This paper studies the user path decision-making method of the mountain city road network from the perspective of network vulnerability. The main innovations are as follows: (1) a user path selection model of mountain city road network based on vulnerability analysis is established. (2) From the two dimensions of network vulnerability and traveler sensitivity, the results show that travelers in different sensitive states have obvious differences in path selection behavior in vulnerable networks.

The results have an important supporting role for the optimization and management of mountainous city road network. In the future, we will further analyze more different characteristics of the mountainous city road network and focus on more kinds of user's path selection behavior.

Data Availability

The data used to support the findings in this study are available from the corresponding authors upon request.

Ethical Approval

All methods were carried out in accordance with relevant guidelines and regulations. All experimental protocols were approved by a named institutional and/or licensing committee.

Consent

Informed consent was obtained from all subjects and/or their legal guardian(s).

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

The work was supported by the National Natural Science Foundation of China (61573076) and Key Scientific and Technological Research Projects of Chongqing Education Commission (KJZD-K201800701).

References

[1] T. M. Alan, C. M. Timothy, and H. G. Tony, "A methodological overview of network vulnerability analysis," *Growth and Change*, vol. 39, no. 4, pp. 573–592, 2008.

[2] J. Sohn, "Evaluating the significance of highway network links under the flood damage: an accessibility approach," *Transportation Research Part A: Policy and Practice*, vol. 40, no. 6, pp. 491–506, 2006.

[3] İ Arşık and F. S. Salman, "Modeling earthquake vulnerability of highway networks," *Electronic Notes in Discrete Mathematics*, vol. 41, pp. 319–326, 2013.

[4] L. Gao, X. Liu, Y. Liu et al., "Measuring Road network topology vulnerability by Ricci curvature," *Physica A: Statistical Mechanics and Its Applications*, vol. 527, Article ID 121071, 2019.

[5] R. Albert, H. Jeong, and A.-L. Barabási, "Error and attack tolerance of complex networks," *Nature*, vol. 406, no. 6794, pp. 378–382, 2000.

[6] H.-y. Yin and L.-q. Xu, "Measuring the structural vulnerability of road network: a network efficiency perspective," *Journal of Shanghai Jiaotong University*, vol. 15, no. 6, pp. 736–742, 2010.

[7] P. Singh, V. S. P. Sinha, A. Vijhani, and N. Pahuja, "Vulnerability assessment of urban road network from urban flood," *International Journal of Disaster Risk Reduction*, vol. 28, pp. 237–250, 2018.

[8] K. Berdica, Z. Andjic, and A. Nicholson, "Simulating road traffic interruptions -does it matter what model we use?, The Network Reliability of Transport," in *The Network Reliability of Transport, Bell*, H. MG and Y. Iida, Eds., Emerald Group Publishing Limited, Bingley, UK, pp. 353–368, 2003.

[9] J. Zhang and M. Wang, "Transportation functionality vulnerability of urban rail transit networks based on moving-block: the case of Nanjing metro," *Physica A: Statistical Mechanics and Its Applications*, vol. 535, Article ID 122367, 2019.

[10] L. Zhang, J. Lu, B.-b. Fu, and S.-b. Li, "Dynamics analysis for the hour-scale based time-varying characteristic of topology complexity in a weighted urban rail transit network," *Physica A: Statistical Mechanics and Its Applications*, vol. 527, Article ID 121280, 2019.

[11] Z. Wu, J. Sun, and R. Xu, "Calculating vulnerability index of urban metro systems based on satisfied route," *Physica A: Statistical Mechanics and Its Applications*, vol. 531, Article ID 121722, 2019.

[12] T. C. Matisziw and A. T. Murray, "Modeling - path availability to support disaster vulnerability assessment of network infrastructure," *Computers & Operations Research*, vol. 36, no. 1, pp. 16–26, 2009.

[13] J. Jing, "A study on robustness in international academia," *Journal of Systems Engineering*, vol. 20, no. 2, pp. 153–159, 2005.

[14] Z. Zhang, M. Li, X. Lin, and Y. Wang, "Network-wide traffic flow estimation with insufficient volume detection and crowdsourcing data," *Transportation Research Part C: Emerging Technologies*, vol. 121, Article ID 102870, 2020.

[15] Q. Wei, H. Z. Jin, C. L. Yao, and J. Guo, "Collapse of complex systems based on brittleness," *Journal of Harbin Engineering University*, vol. 24, no. 2, pp. 161–165, 2003.

[16] X. Y. Wang, Y. Ma, Y. Q. Wang et al., "Traffic flow prediction via spatial temporal graph neural network," *Traffic Flow Prediction via Spatial Temporal Graph Neural Network*, vol. 2020, pp. 1082–1092, 2020.

[17] X. Chen, H. Chen, Y. Yang et al., "Traffic flow prediction by an ensemble framework with data denoising and deep learning model," *Physica A: Statistical Mechanics and Its Applications*, vol. 565, Article ID 125574, 2021.

[18] Y. Yang, Z. Yuan, J. Chen, and M. Guo, "Assessment of osculating value method based on entropy weight to transportation energy conservation and emission reduction," *Environmental Engineering and Management Journal*, vol. 16, no. 10, pp. 2413–2423, 2017.

[19] X. Chen, J. Lu, J. Zhao, Z. Qu, Y. Yang, and J. Xian, "Traffic flow prediction at varied time scales via ensemble empirical mode decomposition and artificial neural network," *Sustainability*, vol. 12, no. 9, p. 3678, 2020.

[20] Z. Pu, Z. Li, R. Ke, X. Hua, and Y. Wang, "Evaluating the nonlinear correlation between vertical curve features and crash frequency on highways using random forests," *Journal of Transportation Engineering, Part A: Systems*, vol. 146, no. 10, Article ID 04020115, 2020.

[21] Z. Li, H. Xu, Y. Wen, and J. Wu, "A deep pedestrian tracking SSD-based model in the sudden emergency or violent environment," *Journal of Advanced Transportation*, vol. 2021, Article ID 2085876, 2021.

[22] M. Q. Lv, Z. X. Hong, L. Chen, T. M. Chen, T. T. Zhu, and S. L. Ji, "Temporal multi-graph convolutional network for traffic flow prediction," *IEEE Transactions on Intelligent Transportation Systems*, vol. 22, no. 6, pp. 1–12, 2021.

[23] G. Blackshields, I. M Wallace, M Larkin, and D. G Higgins, "Analysis and comparison of benchmarks for multiple sequence alignment," *In Silico Biology*, vol. 6, pp. 321–339, 2006.

[24] N. Khademi, B. Balaei, M. Shahri et al., "Transportation network vulnerability analysis for the case of a catastrophic earthquake," *International Journal of Disaster Risk Reduction*, vol. 12, pp. 234–254, 2015.

[25] E. Jenelius and L.-G. Mattsson, "Road network vulnerability analysis: conceptualization, implementation and application," *Computers, Environment and Urban Systems*, vol. 49, pp. 136–147, 2015.